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6. AUTHOR(S)
Ivar Reimanis
John Berger

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Colorado Center for Advanced Ceramics
Colorado School of Mines
1500 Illinois St.
Golden, CO 80401

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13. ABSTRACT (Maximum 200 words)

The research focuses on establishing conditions when interfaces between interlayers are important in governing fracture processes in composites with graded compositions. A theoretical framework is sought that could ultimately quantify the role of interfaces when their presence dominates behavior. Initial work is driven towards establishing general trends. Experimentally, multilayer composites have been fabricated by several techniques that aim at modifying interface characteristics. The competition between fracture at notches of particular depth parallel to the interface and interface fracture is examined. A numerical model is being constructed to obtain crack tip and interface/free edge stress fields to better understand experimental trends. Also, models are being devised to examine how the presence of the interface modifies the stress field of an edge crack parallel to the interface. Experiments in which cracks are extended from notches placed near interfaces have been conducted utilizing optical moiré interferometry (conducted at INEEL). The crack driving force and mode mixity as a function of type of interface and proximity to interface are being determined.

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Final Report
ARO Grant # DAAD19-01-1-0590

The Role of Interfaces in the Fracture of Functionally Graded Materials

PIs: Ivar Reimanis and John Berger
Colorado School of Mines

Statement of Problem Studied

The research focuses on establishing conditions when interfaces between interlayers are important in governing fracture processes in composites with graded compositions. A theoretical framework is sought that could ultimately quantify the role of interfaces when their presence dominates behavior. Initial work is driven towards establishing general trends. Experimentally, multilayer composites have been fabricated by several techniques that aim at modifying interface characteristics. The competition between fracture at notches of particular depth parallel to the interface and interface fracture is examined. A model was devised to examine how the presence of the interface modifies the stress field of an edge crack parallel to the interface. Experiments in which cracks are extended from notches placed near interfaces have been conducted utilizing optical moiré interferometry (conducted at INEEL). The crack driving force and mode mixity as a function of type of interface and proximity to interface were determined.

Summary of the Most Important Results

Efforts have resulted in progress in three main areas. First, a significant effort has been directed to experimental methods for extracting crack driving forces for cracks near interfaces using optical moiré interferometry. A challenge encountered was overcome by developing a new technique to extract fracture parameters from the experimental fringe fields. The main problem was that the displacement data around the crack tip (used to extract the crack driving force, K) crosses the interface when the crack is very close to the interface. There is no known technique to analyze this data across the interface; only methods for a data field in a homogeneous solid exist. A new technique was developed using the *method of fundamental solutions* whereby moiré data across the interface could be used. These experimental results indicate that in certain geometries (a ductile layer sandwiched between two brittle layers) the relative stability of a crack depends on its distance from the interface. Furthermore, there are conditions under which the crack may propagate in mixed mode, though the crack is contained in a homogeneous brittle material.

A second area of progress focused on processing composites of Nb and Al_2O_3 of various compositions. Surprisingly, the mechanical properties of Nb/Al_2O_3 composites have never been evaluated. Fracture testing has shown that there are no significant toughening mechanisms over the entire range of compositions, likely due to the presence of a glassy phase that forms during reaction between native niobium oxide and alumina. An interesting discovery was the extreme difficulty in machining the composite specimens, considering their relatively low fracture toughness (5 – 11 $MPa \cdot m^{1/2}$): Nb/Al_2O_3

particulate composites are extremely wear resistant, and while they may be expensive to machine, they may be excellent in wear resistant applications.

A third area of work has involved establishing the mechanics of interfaces in graded materials. This involved the efforts of researchers in the Computer Science and Mathematics division at Oak Ridge National Laboratory (Dr. Leonard Gray) and a student at Mines (Mr. Adam Goodworth) who analytically calculated the singularity resulting when a bimaterial interface contacts a free surface by a new method. He applied these calculations to an interface for Cu-W composites and found that the zone where the singularity dominates is typically too small to have a significant impact on extension behavior of a crack near the interface.The result is encouraging in the sense that it implies a simplification of near-interface crack studies.

(1) Publications

(a) Papers published in peer-reviewed journals

P. R. Heyliger, H. Ledbetter, S. Kim, and I. Reimanis,"Elastic Constants of Layers in Isotropic Laminates," *Journal of the Acoustical Society of America*, Vol. 114, pp. 2618-2625 (2003).

M. Rudas, M. B. Bush and I. E. Reimanis, "The Kinking Behaviour of a Bimaterial Interface Crack Under Indentation Loading", *Engineering Analysis with Boundary Elements* 28, pp. 1455-1462 (2004).

"Fracture in Nb/Al_2O_3 Particulate Composites", J. Matterson, I. E. Reimanis and J. R. Berger, Ceramic Transactions, Vol. 158, Surfaces, Interfaces and the Science of Joining, ISBN 1-57498-179-X, pp. 81-90, (2005).

H. J. Kleebe, I. E. Reimanis and R. L. Cook, "Processing and Microstructure Characterization of Translucent and Transparent Spinel Monoliths", Ceramic Transactions, Vol.157, Characterization and Modeling to Control Sintered Ceramic Microstructures and Properties, , pp. 61-68, (2005).

(b) Papers published in non-peer-reviewed journals

I.E. Reimanis and J. Chapa-Cabrera, "Cracking in Graded, Layered Structures", Applied Mineralogy, Developments in Science and Technology, Eds: M. Pechio, F. R. Dias de Andrade, L. Z. D'Agostino, H. Kahn, L. M. Sant'Agostino, and M. M. M. Le Tassinari, ISBN 85-98656-01-1, pp. 85-88, (2004).

Ivar Reimanis, H,-J. Kleebe, R. L. Cook, M. Patterson, A. DiGiovanni, "Transparent Spinel Fabricated from Novel Powders: Synthesis, Microstructure and Mechanical and Optical Properties", 10th DoD Electromagnetic Windows Symposium, Little Creek Amphibious Base, Norfolk, VA, May 17-20, 2004.

(c) Papers presented at meeting, but not published

J. R. Berger, Green's functions for Heat Transfer in Anisotropic Graded Solids, *Invited Presentation*, Green's Functions Experts Meeting organized by the National Institute of Standards and Technology, Boulder, Colorado, March 25-26, 2002.

J. R. Berger, "Application of Green's Functions in Functionally Graded Solids", *Invited Presentation*, Mathematical and Computer Sciences Colloquium, Colorado School of Mines, March 1, 2002.

I. Reimanis, "The Strength of Functionally Graded Joints: Crack Paths and Residual Stress", *Plenary Talk*, Functionally Graded Materials 2002, Beijing, China, October 14-18, 2002. (partially funded by DOE/OBES)

K. Rozenburg, I. E. Reimanis, J. R. Berger and E. Steffler, "Investigations of Mechanisms of Crack Propagation Parallel to a Ductile-Brittle Interface" 8th International Symposium on Fracture of Ceramics, Houston, TX February 25-28 (2003).

J. R. Berger, "Crack Tip Stress Fields in FGMs", SIAM Conference on Computational Science and Engineering, Feb 10-13, San Diego, CA 2003.

K. Rozenburg, I. Reimanis and J. R. Berger, "Observations of Crack Growth Parallel to a Ductile/Brittle Interface", ACerS Annual Meeting, April 17-21, 2004, Indianapolis, IN.

Ivar Reimanis, "Residual Stresses in Graded Structures: Effects on Fracture Behavior", *Invited Presentation*, ACerS Annual Meeting, April 21, 2004, Indianapolis, IN.

A. Goodworth, Y.-S. Chan, J. R. Berger, P. A. Martin, and L. J. Gray, "The Free-Edge Singularity Dominated Zone in Copper-Tungsten Graded Materials" IABEM International Conference on Boundary Element Methods, Minneapolis, MN, May 24 – 26, 2004.

J. R. Berger, "Fracture of Copper-Tungsten Layered Composites" *Invited Presentation*, University of Denver, Denver, Colorado, April 30, 2004.

(d) Manuscripts submitted, but not published

M. T. Tilbrook, I. E. Reimanis and M. Hoffman, "Finite Element Simulations of Cracks near Interfaces: Effects of Thermal, Elastic and Plastic Mismatch", submitted to *Journal of the American Ceramic Society* (November 2004).

M. T. Tilbrook, I. E. Reimanis, K. Rozenburg and M. Hoffman, **"**Incorporating Plastic Yielding into Simulations of Crack Propagation near Interfaces", submitted to *Acta Materialia* (February 2005).

(e) Manuscripts in preparation

K. Rozenburg, I. E. Reimanis, J. Berger and M. Tillbrook, "Fracture in Copper-Tungsten Bilayers: Analysis by Optical Moire Interferometry" for *Acta Materialia* (2005)

K. Rozenburg, J. R. Berger, P. A. Martin, and I. Reimanis, "Analysis of Moiré Data for Near-Interface Cracks", for *International Journal of Fracture* (2005).

M. Tilbrook, L. Rutgers, K. Rozenburg and M. Hoffmann, "Fracture in Ceramic Laminates", to be submitted for a special edition in *Composites B: Engineering* (2005).

List of All Participating Scientific personnel supported by this project: Ivar Reimanis (PI), John Berger (PI), Adam Goodworth (M.S: 12/04), Anne Cenedella (graduate student: Ph.D. expected 5/06), Keith Rozenburg (graduate student: Ph.D. expected 12/05), Joe Matterson (graduate student: MS expected 5/05), Nichole Janisch (undergraduate student).